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A FAST, EVOLUTIONARY PROCESS

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LIGHT-ION-INDUCED MULTIFRAGMENTATION: A FAST, EVOLUTIONARY PROCESS

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REACTION DYNAMICS

GeV light-ion-induced reactions offer a unique tool for preparing hot,.dilute nuclear matter. Mediated by multiple N-N scatterings and Δ-resonance excitations, central collisions produce a single, highly-excited source on a very fast time scale (20 - 30 fm/c) [1]. The subsequent evolution of such systems toward multifragment disassembly follows a much different trajectory in the nuclear temperature-density phase diagram than for heavy ions–where significant compression and longer time scales are typically involved. Thus, light-ion- and heavy-ion-induced reactions provide complementary perspectives on attempts to extend our knowledge of the nuclear equation-of-state to a much wider range of temperature and density.

The rapid evolution of light-ion systems into the region of phase instability is illustrated in Fig. 1. Here the central collision trajectory for the 4.8 GeV ^{3}He + Ag reaction is superimposed on the phase diagram for infinite nuclear matter with Z/A = 0.4, as recently calculated by Müller andd Serot [2]. The trajectory is based on BUU calculations of Danielewicz [3,4] and is followed in density (ρ/ρ_0) versus average entropy per nucleon (S/A) coordinates in 4 fm/c steps. In this case, the density is the maximum density (ρ_{max}/ρ_0) at any given time (the average density is somewhat lower). The compression that occurs at early collision times reflects the localized hadronic cascade that develops as the projectile momentum front passes through the target nucleus. Subsequently, the density is rapidly depleted by mass loss during the fast cascade and some expansion, while at the same time, the internal energy and entropy per nucleon grow rapidly. At times of the order of 20 - 30 fm/c, the system begins to cool along a constant S/A line, entering the liquid-gas coexistence and spinodal instability regimes after ~ 40 fm/c. At about this same time, the BUU calculation predicts a significant depletion of the average density in the center of the nucleus, creating a bubble-like structure [4,5].

In Fig. 2, the above time evolution is traced more quantitatively for the 4.8 GeV ^{3}He + Ag reaction [3-5]. Here, we examine the average instantaneous excitation energy/nucleon, $\langle E^*/A\rangle$; maximum density; entropy/nucleon; and mass loss, $\langle \Delta A_{res}\rangle$. During the first 20 fm/c, there is a rapid increase in the deposition energy and entropy per nucleon, accompanied by some localized density compression. Mass loss does not become significant until a reaction time of ~ 20 fm/c is reached. Between 20 - 40 fm/c, the fast cascade produces significant mass loss, causing a rapid decrease in the energy density of the system. At about the same time, the entropy/nucleon approaches a maximum, indicating that the chaotic regime has been reached. In the vicinity of 40 fm/c, the calculation predicts a

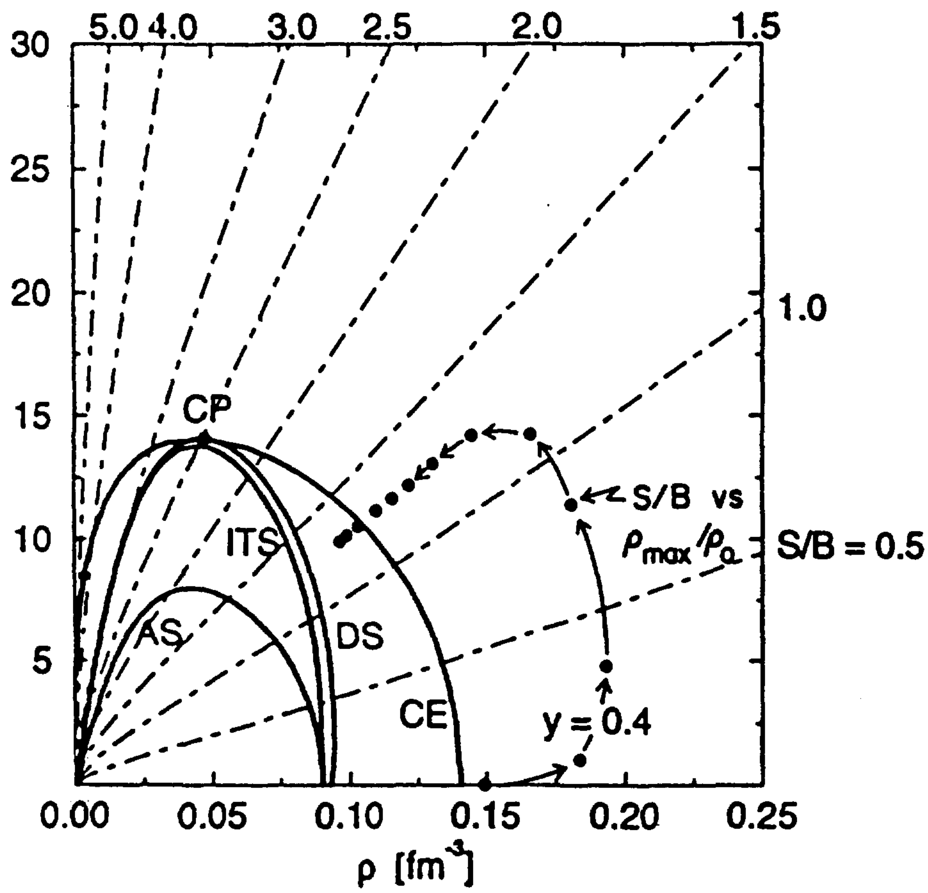

Figure 1. Phase diagram for infinite nuclear matter with $Z/A = 0.4$ in temperature-density coordinates [2]. Values of constant entropy/nucleon are indicated by dashed line. Solid curves denote liquid-vapor coexistence (CE), the diffusive spinodal (DS), isothermal spinodal (ITS) and adiabatic spinodal (AS). The critical point is at CP. Dots indicate trajectory for 4.8 GeV ^3He + ^{108}Ag reaction in steps of 4 fm/c, based on BUU simulations [3,4].

system for which $\langle E^*/A \rangle \approx 9$ MeV, $\langle \rho_{max}/\rho_0 \rangle \approx 0.65$ and $\langle S/A \rangle \approx 1.3$, corresponding to the region of spinodal decomposition in the phase diagram of Fig. 1. As the reaction proceeds, one expects that density/diffusive fluctuations will destabilize such systems, leading to eventual nuclear disassembly, or multifragmentation. Fig. 2 also illustrates the difficulty in determining the excitation energy. For reaction times greater than 40 fm/c, both $\langle E^* \rangle$ and $\langle E^*/A \rangle$ decrease gradually with time. Thus, the question of whether breakup occurs early or late in the history of the hot residue is highly relevant to defining its thermal properties.

From Figs. 1 and 2, it is clear that in order to connect the data with the nuclear phase diagram, it is essential to establish a reliable link between experimental observables and quantities such as the source density and reaction time scales.

Previously, we have shown that the maximum excitation energies determined from the 4.8 GeV ^3He + Ag, Au reactions correspond approximately to those predicted by intranuclear cascade (INC) and average mean field (BUU) calculations [4,6]. These values, $E^*/A \sim 9$ - 11 MeV per nucleon also coincide with the spinodal region of the phase diagram in Fig. 1.

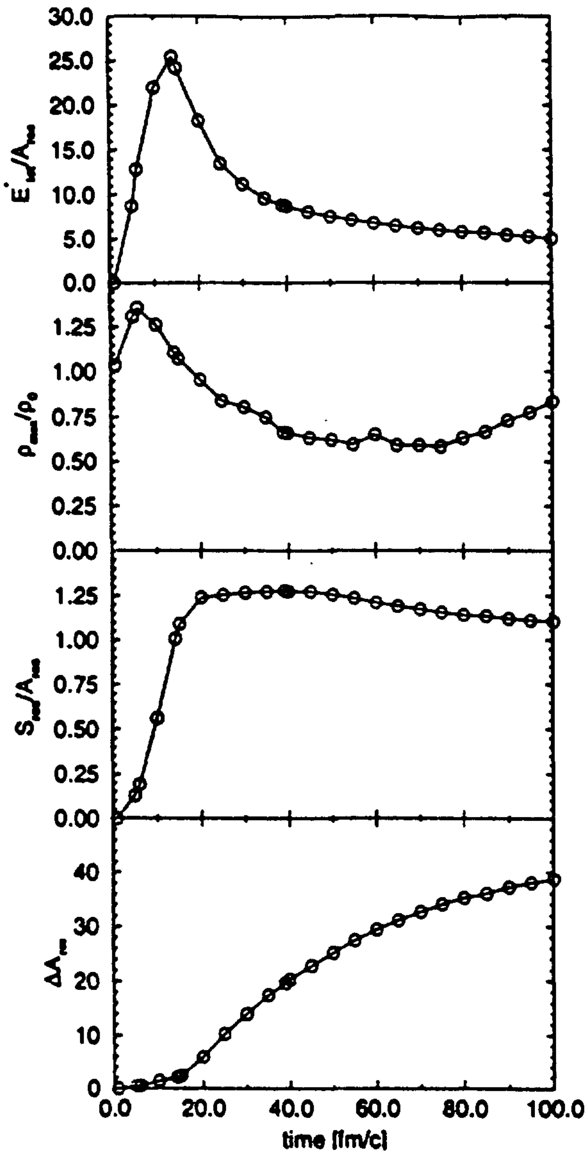

Figure 2. Evolution of average excitation energy per nucleon, maximum density, entropy per nucleon and residue mass loss for the 4.8 GeV ^{3}He + ^{108}Ag reaction [3,4].

EVIDENCE FOR EXPANSION

The question of expansion can be addressed most directly by examining the fragment energy spectra as a function of collision violence [7,8]. For light-ion-induced reactions, the IMF spectra of the most violent events are characterized by Maxwellian-like spectra that peak at energies significantly lower than observed in normal evaporative processes for these systems. This suggests a reduced Coulomb field of the source, implying decreased nuclear matter density. To investigate this question, we have performed two-component, moving source fits to the Z = 3 - 10 IMF data as a function of the total measured charge per event, Z_{obs}. The two sources include a dominant slow source [9] and a fast Maxwellian-like source to account for preequilibrium emission. An important aspect of these fits is that the charge of the emitting source is taken to be $Z_{source} = Z_{target} + Z_{IMF} - Z_{obs}$; i.e. it is assumed that the IMF in question is the last step in a sequential decay mechanism. While oversimplified, this assumption minimizes the extracted source radius from the parametrization; i.e. the corresponding source density ρ/ρ_0 is maximum.

In Fig. 3 values of the fractional Coulomb barrier parameter k_C are plotted as a function of average collision violence $\langle Z_{obs} \rangle$ for the 4.8 GeV ^{3}He + Au reaction. The parameter k_C, which has been averaged over all Z = 3 - 10 fits, is approximately proportional to the inverse of the source radius. With increasing $\langle Z_{obs} \rangle$ values, k_C initially decreases and then becomes constant for $\langle Z_{obs} \rangle = 35$ and greater. This implies that once a sufficiently high degree of excitation is achieved, the breakup geometry does not change appreciably. To obtain an estimate of the breakup density, we assume that the lowest excitation energies, i.e. $\langle Z_{obs} \rangle = 5$, involve emission from a source at normal nuclear matter density, $\rho/\rho_0 = 1$. With this normalization, the corresponding densities for more violent collisions can be calculated (solid dots in Fig. 3). As shown, the results yield an upper limit for the breakup density of $\rho/\rho_0 \leq 1/3$ for $\langle Z_{obs} \rangle \geq 35$.

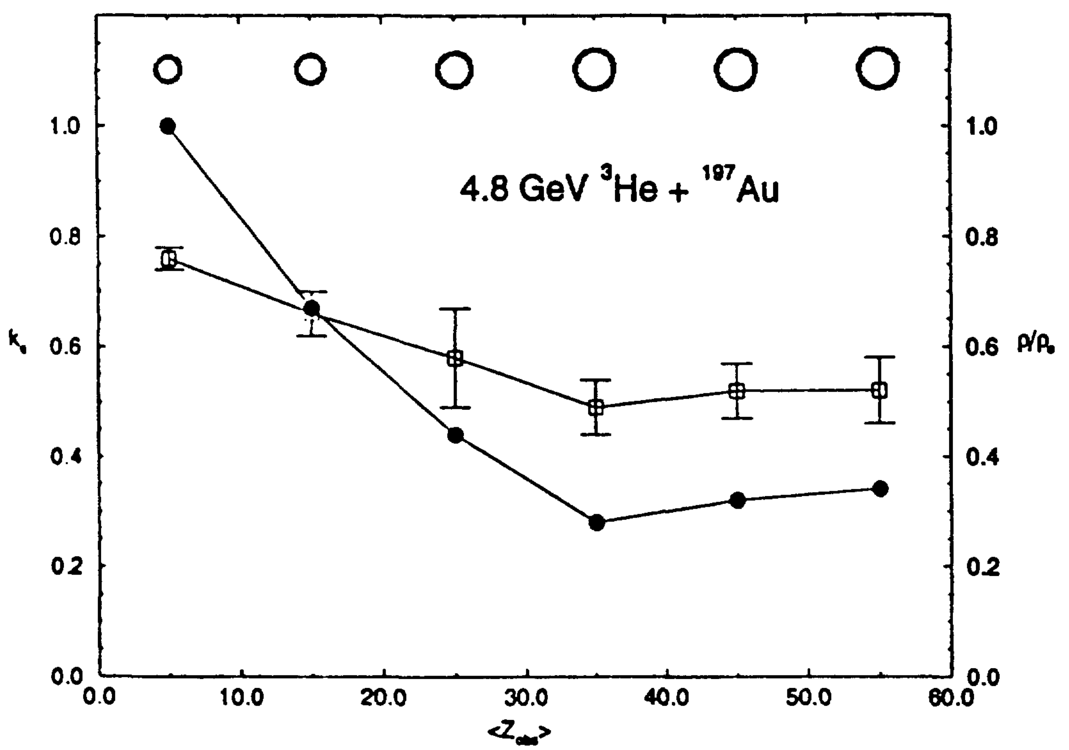

Figure 3. Plot of Coulomb parameter k_C from two-component moving-source fits as a function of average $\langle Z_{obs} \rangle$ bins for the 4.8 GeV ^{3}He + ^{197}Au reaction (open points). Closed points indicate corresponding source density (right-hand scale).

This analysis, plus the isotropic nature of the high-multiplicity events [8], indicates that multifragmentation occurs from a highly-excited chaotic system that has undergone significant expansion prior to breakup—or some comparable mechanism that involves dilution of the Coulomb field of the emitting source. The time-dependent geometry of the source may also be an important factor, as suggested by the density profile in Fig. 2.

TIME SCALE

In order to evaluate the disassembly time sequence, both small- and large-angle correlations of IMFs have been investigated. The former yields information relevant to the emission time scale and the latter to the question of sequential versus simultaneous emission.

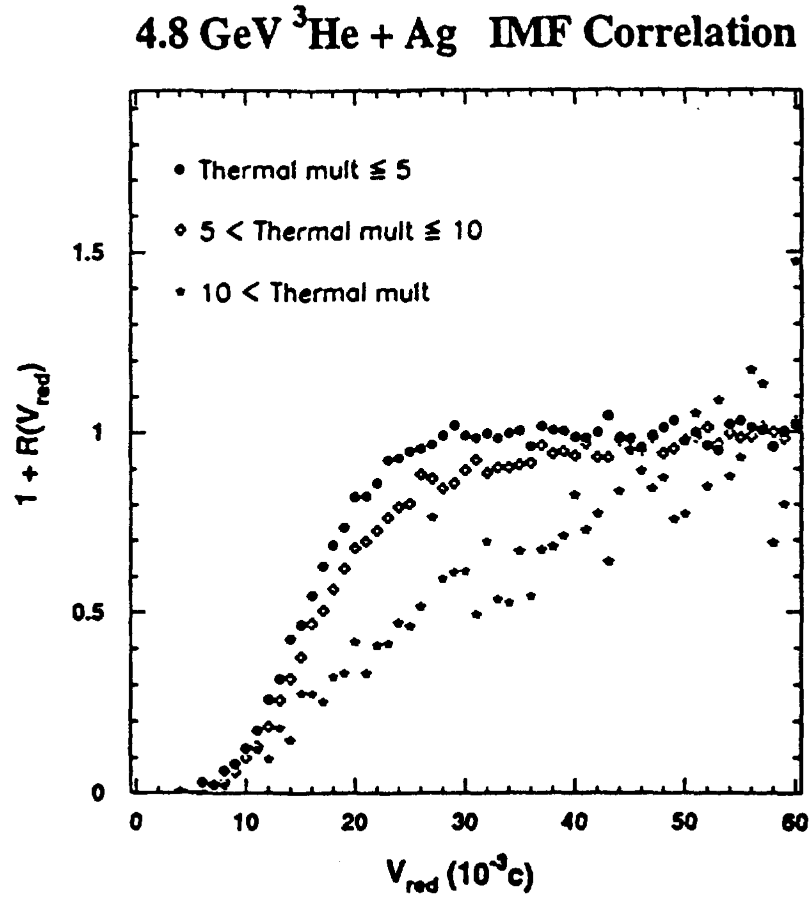

Figure 4. **Small-angle correlations as a function of reduced velocity for three thermal multiplicity bins. Data are for 4.8 GeV ^{3}He + ^{nat}Ag reaction.**

Small-angle correlations [10] are sensitive to the time delay between two IMFs emitted at small angles with respect to one another. For fragments with similar velocities and small delay times, mutual Coulomb repulsion will result in a suppression of the correlation function at small angles. In Fig. 4, correlation functions 1 + R for the 4.8 GeV ^{3}He + Ag reaction are plotted as a function of reduced velocity v_{red}, for three different cuts on deposition energy. Here collision violence is gauged in terms of the multiplicity of thermal ejectiles [6], M_{th}. The parameter M_{th} scales closely with Z_{obs}, but has the advantage of eliminating preequilibrium fragments from the analysis. For the two lower M_{th} gates, three-body Coulomb calculations (not shown) are consistent with a time scale of $\Delta\tau \sim 100$ fm/c, consistent with heavy-ion multifragmentation results. However, for the largest thermal multiplicities, the "Coulomb hole" is among the largest yet observed, corresponding to a negligible emission time difference, $\Delta\tau \approx 0$. Thus, correlations for large M_{th} values and corresponding three-body Coulomb trajectory calculations are consistent with a picture in

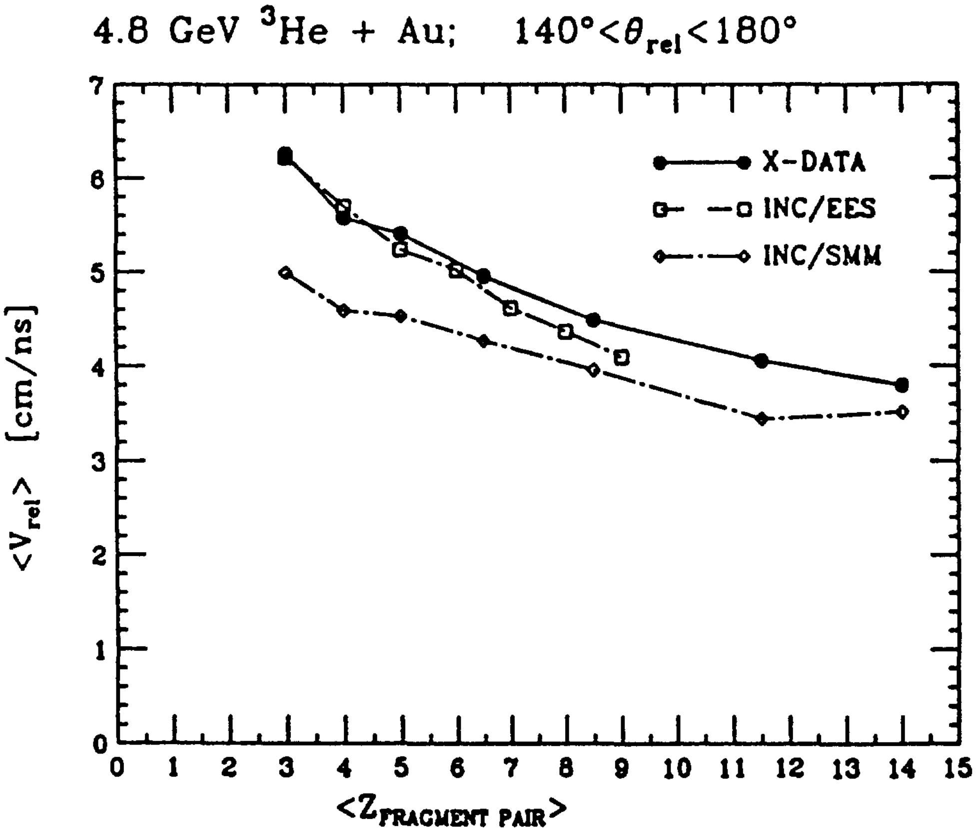

Figure 5. Large-angle correlation data (solid points) for identical fragment pairs as a function of fragment Z. Squares show results for INC/EES model and diamonds represent the INC/SSM result.

which the time difference between successive IMFs is negligible. This implies that at least for the final breakup stages, the disassembly is nearly simultaneous.

The large-angle correlations permit a more direct comparison between time-dependent [11] and simultaneous [12-13] models of multifragmentation. Two model calculations have been performed, both of which assume expansion of the source: the time-dependent expanding emitting source model (EES) of Friedman [11] and the simultaneous statistical multifragmentation model (SMM) of Botvina [12]. In both calculations, the excitation energy distribution of the fragmenting species is that predicted by the intranuclear cascade (INC) code ISABEL [14]. The INC/EES model has been shown previously to give a good account of the multiplicity distribution and energy spectra in these reactions [15].

In Fig. 5, the average relative velocities are plotted for pairs of identical fragments emitted between $140° \leq \theta \leq 180°$ in the 4.8 GeV ^{3}He + Au reaction. Also shown are predictions of the INC/EES and INC/SMM calculations, using default parameters in both multifragmentation codes (i.e. $\rho/\rho_0 \approx 1/3$ at breakup). The INC/EES model clearly provides better agreement with the data, supporting an evolutionary model in which energetic light fragments are emitted early in the expansion/cooling phase, followed by eventual multifragmentation of the most highly excited residues. This scenario does not preclude the possibility that the SMM model may describe the final disassembly stage, but does argue for the necessity to account for sequential fragment emission (and mass/charge loss) during expansion.

SUMMARY

The current light-ion multifragmentation data from ISiS provide evidence for emission from a dilute nuclear system, presumably due to expansion. Fragment-fragment correlation studies argue for a fast, evolutionary multifragmentation mechanism in which energetic light fragments are emitted during the expansion phase, followed by simultaneous breakup of the hot, dilute residue. Based on BUU simulations and the time scales implied by small-angle correlation functions, the full temporal evolution of such systems occurs on a time scale of $\tau \sim 50$ - 100 fm/c.

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